Searches for SUSY with the ATLAS detector

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Abstract. We present a review of the SUSY search strategies in ATLAS in conjunction with a readiness of the detector systems for first collision data in 2009 fall. Commissioning was performed with the LHC single beams and the cosmic ray data in 2008. The talk covers the analysis strategies based on the large E_T^{miss} plus high p_T multi-jets signature in which the number of methods are investigated to extract background estimation from real data. The expected discovery reach with inclusive analysis is shown. The review also covers the special signature searches for certain SUSY scenarios, where specific detector components play a crucial role in detecting and measuring them.

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INTRODUCTION

The world's most exciting moment is finally about to happen this year 2009. The Large Hadron Collider (LHC) at CERN is expected to deliver a few 100 pb^{-1} of integrated luminosity to experiments in the first year(s). The ATLAS collaboration is now ready for the first *pp* collision data from LHC, after 15 years of preparation and integration of the detector systems. The theoretical potential for discovering physics beyond the Standard Model (SM) is quite high, especially the supersymmetry (SUSY) is one of the highly motivated scenarios expected to be discovered at LHC. It is vital to corroborate our final readiness before the dawn of new physics, on both the detector systems and the analysis strategies.

At LHC energy regime, the SUSY production process is dominated by the strongly interacting particles, namely the squarks and gluinos, which are typically the heaviest among the SUSY particles. The cross section is fairly independent from the detail of phenomenology models behind. This allows us to generalize our SUSY search strategies. In the context of Minimal Supersymmetric extension of the Standard Model (MSSM) with R-parity conservation, these pair-produced SUSY particles (majority of which are colored) decay to lighter particles. They cascade down until they reach the lightest SUSY particle (LSP). Therefore rather complex event signatures are typically expected. The details of the cascade decays are functions of model parameters, which cannot currently be predicted. Our strategies should rely on the robust signatures which cover large classes of models, and in the same time it should be clearly distinctive from the SM backgrounds. Therefore, in our base analysis we look for the signatures as,

$$\text{large } E_T^{\mathrm{miss}} + \text{high } p_T \text{ multi-jets} + (\text{leptons}, b\text{-jets}, \tau\text{-jets}) \tag{1}$$

and in some cases, photons or long-lived SUSY particle signatures exist on top of these basic requirements. Obviously good performance of the detector ingredients is
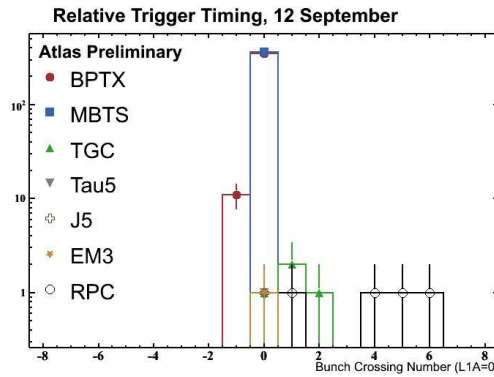
Relative Trigger Timing, 12 September

FIGURE 1. Timings of various trigger menus at the 3rd day of the Sept.'08 commissioning, relative to the MBTS timing in unit of bunch crossings.

the key for the early confirmation of SUSY. The questions we must ask are: (i) Are the detectors ready for the first collision data? Do they achieve expected performance in commissioning? (ii) Are we able to get SM backgrounds under control? Could we estimate the background without relying too much on the Monte Carlo? (iii) If special signatures exist on top of the basic requirements, are we able to detect them? The current answers for these questions are addressed in this talk.

STATUS OF ATLAS DETECTORS IN COMMISSIONING

The ATLAS detector is a multi-purpose detector systems composed of 4 major components: inner trackers, calorimeters, muon spectrometers and magnets, whose detailed description can be found elsewhere [1] (and references therein). The most important tasks which have to be carried out in the commissioning phase are the calibrations and the alignments. These have to come before any physics measurements. There are numbers of in-situ calibration/alignment menus scheduled with the early physics data which one can address when the collision data arrives. For instance, we use $Z \rightarrow ee$, J/Ψ samples to determine the e/γ energy scale . However even before arrival of collision data, the current commissioning programs on cosmic ray data, single beam data from 2008, and the stand-alone calibration/alignment systems, can address the performance on track alignments, azimuthal asymmetry/uniformity of Calorimeters, muon system alignment, etc.

Commissioning with cosmic rays. The activity started as early as 2005 in parallel with the detector installation. In the last few years, the work evolved from single component operations to combined detector running. With significant number of events, we were able to gain experience in detector operation and control, DAQ and analysis chain, together with the understanding of in-situ performance. Integrated cosmic data from the combined commissioning since Sept. 2008, exceeded 200M events, allowing fairly precise performance control.
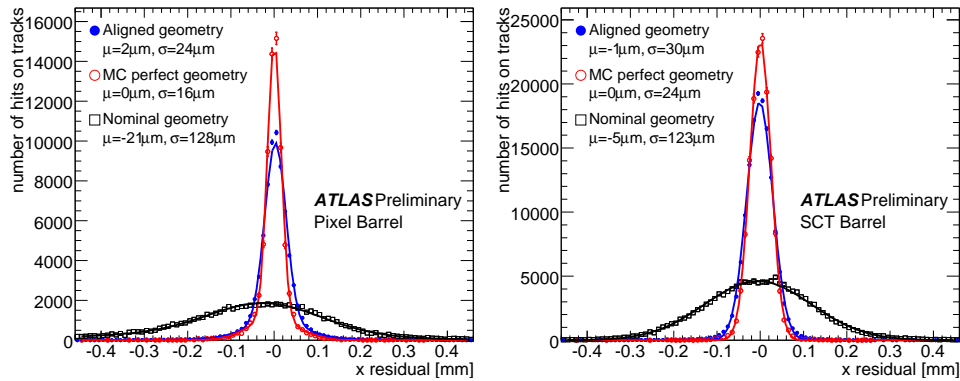
FIGURE 2. Residual distributions of inner detectors for cosmic ray data; (left) Pixel tracker for precision coordinate in barrel region, (right) SCT for precision coordinate in barrel region. (red) distribution from MC simulation obtained with perfect geometry: (black) before the alignment, (blue) after the alignment

Commissioning with single beam. As described in more detail in [2], the first proton beams in LHC rings were circulated for ten days starting on Sept. 10th 2008. ATLAS made a good use of this opportunity for timing adjustments for trigger and detector system. Trigger timing was firstly adjusted using Minimum Bias Trigger Scintillators (MBTS) located at the surface of End-cap electromagnetic Calorimeters, and the beam timing pick-up (BPTX) located at upstream beam line 175*m* away from ATLAS. Figure 1 shows the situation on the third day, where various LVL-1 trigger timings are shown with respect to the MBTS. Relative timing between MBTS and BPTX, and the beam quality had been significantly improved in a short time. Also with so-called "splash" events (beam dump collimator were placed 140*m* upstream from ATLAS), one could align the timing of large detector volumes within 1 *ns*.

Readiness of the inner detector. The alignment of the ATLAS Inner detector components (from inside: Pixel, SCT, TRT) is a crucial task in reaching the design performance. The procedure is based on the minimization of hit residuals for high p_T tracks, e.g. cosmic muons. Figure 2 shows the residuals for Pixel ($\sigma = 24\mu m$) and SCT ($\sigma = 30\mu m$). The residual widths after the alignment are quite close to the performance which one could expect with perfect geometry in simulation. The same is true for the TRT. The fraction of masked channels due to the hardware failure is low, Pixel (well below 0.02%), SCT ($\sim$1% in Barrel, $\sim$3% in End-cap, aiming $< 1\%$ in 2009). The efficiency is high, i.e. Pixel($\sim$ 99.8%), SCT($>\sim$ 99.0%). With the TRT, the transition radiation from high p_T muon (> 100GeV) is also observed, the rate agrees well with the test beam result.

Readiness of the Calorimeters. The uniformity and stability in operation are the most important performance parameters for calorimeters with in-situ cosmic ray measurements before the collision data. Figure 3 shows the uniformity measurements (left) in LAr EM calorimeter. The most probable value (MPV) followed the calorimeter cell depth shape. Good agreement with simulation is obtained at the 2% level (right) In the tile hadron calorimeter, the uniformity across the partition is confirmed to be less than
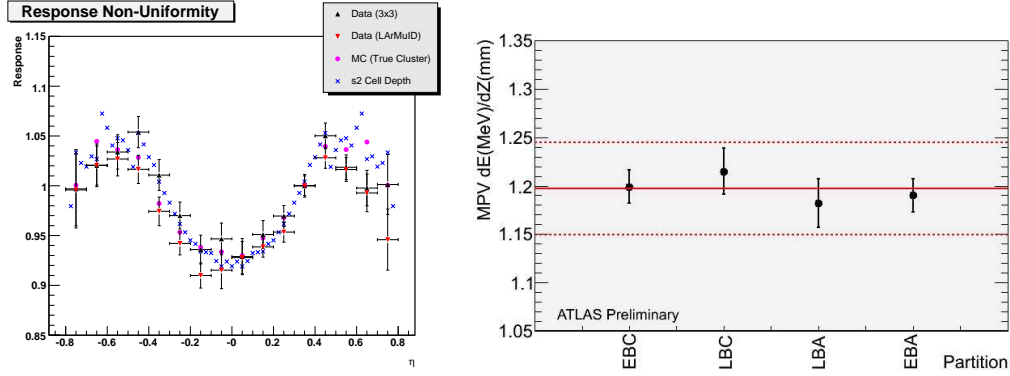
FIGURE 3. Uniformity of the calorimeters: (left) the energy response MPV as a function of η for LAr Electromagnetic calorimeter in barrel region. Two data types with different cluster algorithms, one Monte Carlo simulation, and geometrical cell depth are shown. These are normalized to the points in $0.3 < \eta < 0.4$. (right)the most probable dE/dx value per partition (in beam direction) obtained with single beam. The detector partitions are calibrated with embedded γ-ray sources.
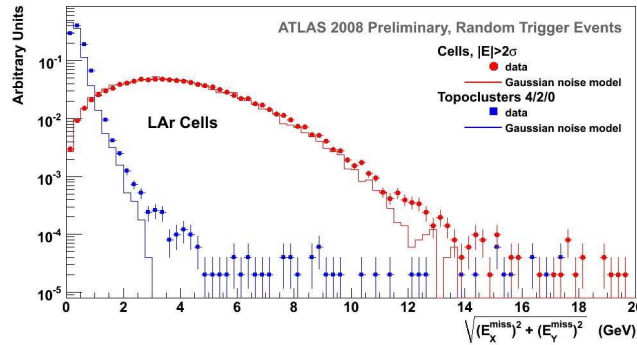

FIGURE 4. E_T^{miss} distributions from random trigger events. Two algorithms (red: cell-based, blue: topo-cluster) are shown. Data points represents the measurements, while lines illustrate the expected distributions with Gaussian noise model. Only cells from the LAr EM calorimeter are used in this plot.

4%. Concerning the stability, various values are monitored during the operations. For instance, the pedestal variation of EM calorimeter was confirmed to be ± 1MeV over 5 months. The noise distribution of the hadron calorimeter obtained during single beam run is comparable to the one obtained during the cosmic ray measurement. These clearly demonstrate the readiness of the calorimeters for the collision environment.

Missing E_T performance. Although the full commissioning of E_T^{miss} performance has to wait for the collision data, the tests on noise suppression of the cluster algorithms, detector performance checks can be carried out at present with a randomly timed trigger. Figure 4 shows the E_T^{miss} distributions for the two main E_T^{miss} calculation algorithms adopted in ATLAS, namely (i)*the cell based algorithm*; with a simple model useful in assessing the basic calorimeter performance, (ii) *the topological clustering algorithm*; with better noise suppression and resolution. The tests were carried out with nearly full
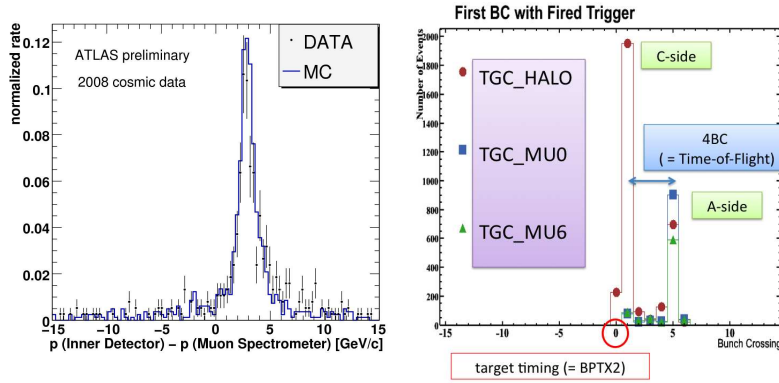
FIGURE 5. (left) difference in cosmic ray momentum measurements between inner detector and the muon spectrometer for matched tracks. Expected energy loss in Calorimeter (about 3GeV) and width of data (points) is well described by MC simulation (solid histogram). (right) LVL-1 muon trigger timing in End-cap region for beam halo events. The beam halo particles penetrate ATLAS detector from C-side (Geneve side) to A-side (Mt. Jura side). The event rate of three trigger menus (different by matching criteria) are shown. In order to bring A-side to proper timing, the timing is shifted by -5 bunch crossing units after this measurement.

detector readout, with 50k events taken with random trigger. The Gaussian noise model (solid histograms) describes the data well, which illustrates the degree of understanding of the detector noise at the current stage.

Muon system. The alignment of the muon system in ATLAS is performed with the optical system [5]. The quality is monitored with the saggita distribution at the middle layer of the system. The mean values are fairly close to zero $(134(15)\mu m$ for Barrel (End-cap)). Further improvement expected with the help of tracking information. The cosmic rays penetrating near the interaction point give a good opportunity to compare the muon system against the inner tracker. Figure 5 (left) shows the difference in momentum measurements between the two systems. The energy loss and the resolutions are well reproduced by the simulation, which is also true for the distributions of the differences in the azimuthal angle between the two systems. Figure 5 (right) is a trigger timing performance plot for the End-cap muon system. The detector timing (within one bin), relative (between C and A sides) and absolute (with respect to the BPTX) timings, are all under good control.

In summary, the systems in ATLAS are all ready for the first collision data. More details of the commissioning can be found in another talk [4].

STRATEGY OF FINDING SUSY IN INCLUSIVE SEARCH

The SUSY analysis perspectives presented here are based on the ATLAS data preparation paper [3]. Hence, the analyses assume $\sqrt{s} = 14$TeV and $\int L = 1$fb^{-1} (Initially the LHC will run at lower energies, see [2]). ATLAS intends to cover all the possible SUSY event topologies, that is different NLSP types, number of jets, number of leptons, also consideration of the requirements on taus, b-jets, photons, and long-lived particles. On
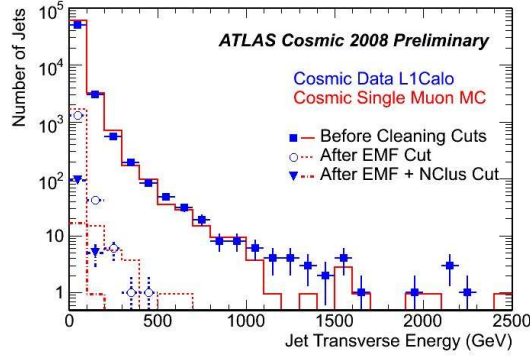
FIGURE 6. The transverse energy distributions of cosmic rays reconstructed as Jet. Data and MC simulation are shown with blue square points and red solid line respectively. Also shown are the data points and the respective MC predictions after the event filter for cosmic rays.

top of these, SUSY breaking scale and model dependent parameters add further complexity. Although the phenomenological model independent approach is desirable, it is impossible to cover all these without any assumption. We therefore base our analysis strategy on modes where we have a good confidence in background estimation. Thus we categorize the event signature by number of leptons. Accordingly the major background sources change which requires respective estimations.

0-lepton mode. Here a control of the huge QCD background is the most important. The fake E_T^{miss} caused by accelerator, cosmic rays, detector effect/failure needs to be understood. Those local malfunctioning of detector, e.g. noisy/dead cells, or HV trips, etc, are monitored and rejected event by event basis. The bad runs will be dealt with run database. Concerning cosmic rays, ATLAS already has a good description of data with Monte Carlo simulation as one can confirm in Fig. 6. The cleaning cut on these events, using energy fraction in EM component, works effectively, which is also reproduced by simulation. The detector effect on E_T^{miss} caused by the jets falling in poorly instrumented region is dealt with the cut on $|\phi^{jet_i} - \phi^{E_T^{miss}}|$, as the E_T^{miss} is expected to align with the leading p_T jets in such events. After all these considerations plus the standard SUSY selections, comparable contributions from $t\bar{t} + jets$, $W + jets$, and $Z + jets$ processes are expected. However the contribution from QCD (which current simulation suggest is $< 5\%$) has the largest uncertainties, where it is difficult to perform a realistic estimation with Monte Carlo simulation, as the E_T^{miss} could come from the far tail of the detector response. ATLAS developed various procedures to estimates the QCD contributions in the SUSY signal regions directly from the collision data (data driven estimate). One of which uses three-jet events to estimate the E_T^{miss} tail created by jet energy fluctuations [6]. Figure 7 (left) demonstrates this method. Data driven estimates for $Z \to \nu\nu$, W, $t\bar{t}$ have also been developed [3].

1-lepton mode. With the requirement of one lepton, in spite of a smaller cross section, we can expect better control over many of the backgrounds. Here we add the isolated lepton requirement and the cut on transverse mass (M_T). At this point,
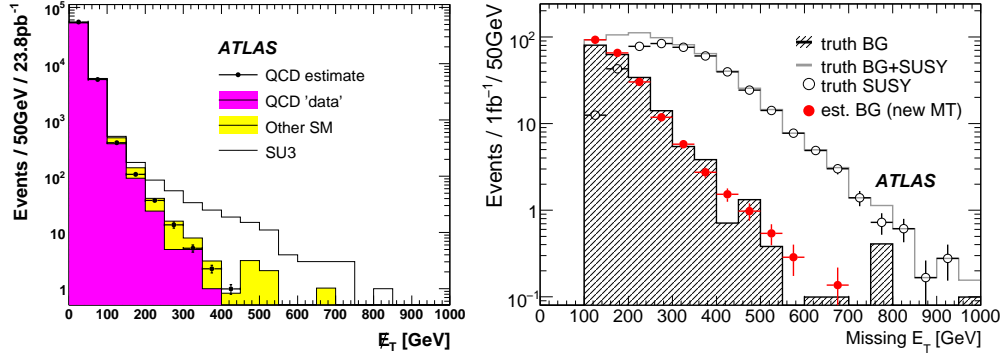
FIGURE 7. Background estimation from the data driven methods: (left) E_T^{miss} distributions of SM backgrounds and estimation of QCD contribution described in the text after applying 0-lepton mode jet cuts for SUSY analysis. Also shown is the distribution of a typical SUSY signal. (right) E_T^{miss} distributions of SM backgrounds and estimation from the new M_T-method. The 1-lepton mode SUSY event selections are applied.
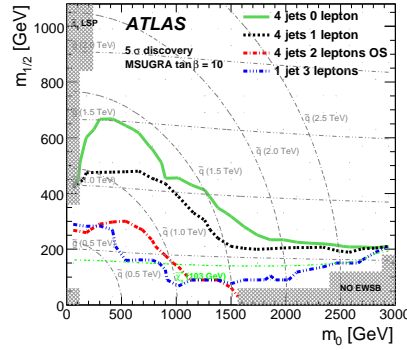

FIGURE 8. Discovery reach of inclusive SUSY search in mSUGRA parameter space assuming $\sqrt{s} = 14\,\text{TeV}$ and 1fb^{-1} integrated luminosity.

$t\bar{t} + jets$ is dominant, while $W + jets$ is important in the high E_T^{miss} tail in the remaining background. The QCD background appears to be negligible. The data driven technique is developed to use the control region (low M_T region) to evaluate the normalization and shape of background in signal region, called, 'M_T method'. Further improvement is applied to deal with the case where the SUSY signals contaminate the control region (where background would be over estimated with naive M_T method). As seen in Fig. 7 (right) the new method successfully estimates the size of the background contribution. The studies on the 2-lepton mode, higher multi-lepton mode, τ signature, and with b-jets are also carried out in ATLAS which are reported in the other talks [8, 10].

Inclusive reach in SUGRA parameter scape. After all these considerations, the SUSY discovery reach for 14TeV, 1fb^{-1} is obtained, taking into account the expected uncertainties on SM backgrounds using 1fb^{-1} of integrated luminosity [7]. The systematic errors are estimated to be 50% on QCD processes, and 20% on $t\bar{t}, W, Z$+jets. This is
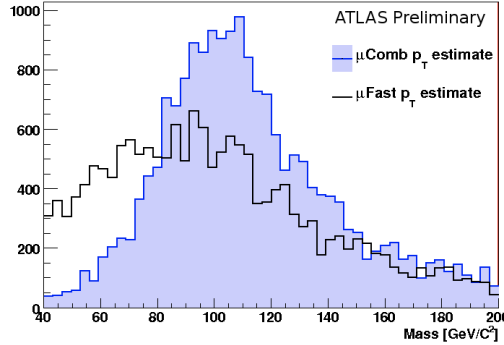
FIGURE 9. The mass distribution obtained at the LVL-2 trigger stage. $M_{\tilde{\ell}} = 100\text{GeV}$, 500pb^{-1} luminosity is assumed. Cuts of $p_\text{T} > 40\text{GeV}$, $\beta_{measured} < 0.97$ are applied. Background from the inclusive single muon events -not shown here- has a tail up to 80GeV in mass, which can be effectively eliminated in this case.

illustrated in Fig. 8, where 4 jets plus different lepton requirements are shown. It is also seen that multiple signatures are expected in most of the parameter space, meaning the redundant analysis is possible.

With the 10TeV and 100pb^{-1}, lower cross sections and worse background control are anticipated, which would naturally degrade the reach. However it is still expected to go beyond Tevatron limit. Exclusive measurements are not covered in this review. The reader is referred to other dedicated talk [9].

SUSY WITH SPECIAL SIGNATURES

In addition to the SUSY signatures with jets and E_T^miss, ATLAS will search for the various well-motivated physics, which predict characteristic signatures e.g. GMSB, AMSB, Split SUSY, RPV, etc. Regardless of the models considered, the signatures can be generally categorized in terms of NLSP type and lifetime. In each category, the relevant detector component is different. In most of the models, the signal has basis SUSY characteristics such as multi high-p_T jets, large E_T^miss, thus such signals has high efficiency with standard trigger menu for SUSY. The trigger menu based on these special signatures adds redundant triggers. In some cases, the dedicated menu and algorithm have to be prepared for cases, when the basis SUSY signature is missing.

One such scenario is the additional high-p_T photons in GMSB models with a $\tilde{\chi}_1^0$ NLSP. There we expect high-p_T jets, large E_T^miss, then 2 high-p_T photons, hence we expect very small SM backgrounds. With a good control over the fake photons, the potential for early discovery is high. In GMSB models, NLSP could be long-lived, then the photon no longer points back to the interaction point. ATLAS is equipped with finely granulated EM calorimeter layers in η direction, and also these have a good timing resolutions. Hence the detector is sensitive to 'non-pointing' photons and the lifetime of the NLSP could be measured [11].

Another scenario is heavy meta-stable charged particles which penetrate through

ATLAS rather like high-p_T muons [12]. Uncolored particles, such as sleptons, can be distinguished from muons since they would have small β and have significant delay in TOF. Special trigger and reconstruction algorithm are essential to detect such particles. In ATLAS, special menu is prepared to select the low β, high mass particles at the LVL-2 trigger stage, as seen in Fig. 9.

At Event Filter (LVL-3 trigger), finer mass reconstruction is possible, where the mass resolution for 100GeV slepton would be 16%. Yet another unique signature is foreseen with so called 'R-hadrons' with color interactions in detector. For these one would expect charge flips inside calorimeter, invisible tracks inside inner trackers, etc [13]. There are other unique signatures which ATLAS will pursue. (One such scenario is R-parity violation [14])

CONCLUSIONS AND OUTLOOK

ATLAS is finishing its final tests on detectors, DAQ, and online systems using cosmic rays and single beam data taken during 2008/2009. Analysis techniques in estimating the backgrounds using real data have also been developed and are maturing for practical use, still new ideas and improvements are evolving. We confirmed that there is a good potential of discovery at 10TeV, 100-200pb^{-1} . Also preparations for SUSY signals accompanying special signatures are ready.

We look forward to bringing the big news and surprises in next year.

ACKNOWLEDGMENTS

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